The multi-phase ISM of radio galaxies

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Chapter 1

Introduction

1.1 AGN in galaxy evolution: a fundamental piece of the puzzle

We know that the galaxy population in the local Universe is divided into galaxies that are actively forming stars (i.e. late-type galaxies, LTG) and more massive galaxies with little on-going star formation (i.e. early-type galaxies, ETG). According to our current understanding, a galaxy that is actively forming stars evolves by increasing its mass via cold gas accretion from the cosmic web and via mergers with other galaxies. When this galaxy approaches a critical mass its growth stops, the star formation is quenched and the galaxy ages without forming new stars (see e.g. Lilly et al. 2013). What quenches massive galaxies is still a matter of debate and one of the most likely processes is the feedback given by the energy released by the central supermassive black hole (SMBH).

Massive galaxies are known to host a SMBH at their center and when material accretes onto it, part of the gravitational energy of this process can be converted in radiation. This can much exceed the energy emitted by the surrounding stars in the host galaxy and when this happens, the SMBH is considered active: an active galactic nucleus (AGN).

AGN are among the most powerful sources of energy in the Universe and their emission covers the entire electromagnetic spectrum, from the radio band up to γ-rays. The first studies of these objects date back to the work of Seyfert (1943) and Baade & Minkowski (1954).

A SMBH is believed to go through multiple phases of activity during the life of the host galaxy (Marconi et al. 2004; Best et al. 2005; Schawinski et al. 2015), but the conditions which trigger this activity, and how often these phases occur, are not yet fully understood. The nuclear activity and its cycles have become particularly relevant because, in recent years, an increasing number of observations stressed the existence of an intimate relation between AGN and their host galaxies.

A correlation between the properties of SMBH and their host galaxy bulges has been found (Kormendy & Ho 2013). More strikingly, the evolution of galaxies, traced via their star formation history, and of SMBH, traced via the AGN activity, are remarkably similar across cosmic times (Shankar et al. 2009). For these reasons, besides being interesting objects in their own right, AGN have gained increasing attention and relevance in galaxy evolution studies.

Observations have confirmed that the energy released by an active nucleus is effective in heating and/or expelling gas from the interstellar medium (ISM) of the host galaxy (Silk & Rees 1998; Fabian 2012). This effect is known as AGN feedback and, nowadays, is routinely included in cosmological simulations aimed at reproducing the observed properties of the current population of galaxies. In particular, AGN feedback is invoked to prevent gas accretion onto massive ETG and quench their star formation (Benson et al. 2003a; Bower et al. 2006a; Bongiorno et al. 2016). Moreover, it can explain the observed scaling relations between the central black hole mass and its host galaxy properties (Silk & Rees 1998; Fabian 1999; King 2003; Granato et al. 2004; Di Matteo et al. 2005).

Active nuclei can manifest themselves in different ways at different frequencies. In the optical band, AGN have been identified, and separated from star forming galaxies, by studying the ionization state of the ISM via flux ratios between pairs of emission lines. The work by Baldwin, Phillips and Terlevich introduced this approach for the first time, giving the name to the so-called BPT diagrams (Baldwin et al. 1981). In optical AGN, the excitation of the optically emitting gas is determined by the ultraviolet (UV) radiation from the SMBH, although ionization connected to fast shocks can also be present. The ionized gas is particularly relevant to the work presented in this thesis, and in Chapter 4 and Chapter 6 I use BPT diagrams, together with models, to study the physics of gas under the influence of the energy released by the AGN. Active nuclei are also able to launch powerful two-sided jets of relativistic particles. These jets are mostly bright in the radio band, they can extend to galaxy scales and beyond and are a distinctive feature of the so-called radio AGN. Radio AGN inject a significant amount of mechanical energy into the ISM of the host galaxy via jets. The expansion of these jets can accelerate gas at high velocities, producing massive gas outflows.

Studies at different wavelengths favored the appearance and the proliferation of different AGN classes (see Padovani et al. 2017, for a review). Many efforts have been undertaken to contain the diversity of object types and to bring together the results from the different studies. Historically, the most significant step in this direction has been the 'unified AGN scheme' which grouped different classes of AGN based on their orientation (e.g. Antonucci 1993; Urry & Padovani 1995; Netzer 2015). This scheme distinguishes between the so-called Type 1 and Type 2 AGN, these are intrinsically the same objects that appear different due to their orientation with respect to the line of sight (see Fig. 1.1). More recently, the unification scheme has been integrated in a broader scheme connecting the differences between the observational properties of AGN to the way material accretes onto the SMBH.

In this thesis I study the ISM of galaxies hosting a radio AGN in relation to both the SMBH feeding an the AGN feedback. In what follows I am going to describe the properties of the two main classes of AGN defined based on their accretion mode (Sec. 1.1.1) and the physical processes involved in the AGN feeding and feedback (Sec. 1.1.2). Then, in Sec. 1.2, I will focus on radio AGN and on the relevance that the radio jets have in disturbing the surrounding ISM on galactic scales. Finally, in Sec. 1.3 I will discuss gas outflows, one of the main observational evidence of the AGN feedback. These outflows are observed in different gas phases and I will give particular attention to the outflows driven by the expansion of radio jets.

1.1.1 AGN classification: radiative-mode vs. jet-mode

More than others, the study of Best & Heckman (2012) has been fundamental in showing that low-redshift AGN can be grouped in two main categories (see Heckman & Best 2014, for a comprehensive review on this topic). One class includes the so-called 'radiative-mode' AGN, objects that emit most of their energy in the form of radiation produced by the accretion of gas onto the SMBH. On the other hand, there are AGN which produce little radiation and whose main energy output channel is two-sided particle jets. These are called 'jet-mode' AGN. As described by Heckman & Best (2014), the predominant form of energy produced by black holes switches from radiation to jet energy at the highest stellar galaxy masses ($> 10^{11.5}$ M$_\odot$), corresponding to a black hole mass $> 10^9$ M$_\odot$.

In Fig. 1.1 the main physical components of these two classes of objects are outlined. The accretion rate of a SMBH is usually expressed in terms of the Eddington accretion rate, using the ratio between the AGN bolometric luminosity ($L_{\rm Bol}$) and the Eddington luminosity ($L_{\rm Edd}$) of the SMBH [1]. The two AGN modes are intimately related to the way the SMBH accretes material. In what follows I describe the main components of radiative-mode and jet-mode AGN.

[1]The Eddington luminosity is the luminosity beyond which the radiation pressure overcomes the gravitational force of the black hole. $L_{\rm Edd} = 3.3 \times 10^4 M_{\rm BH}$, where both the luminosity and the black hole mass are expressed in solar units

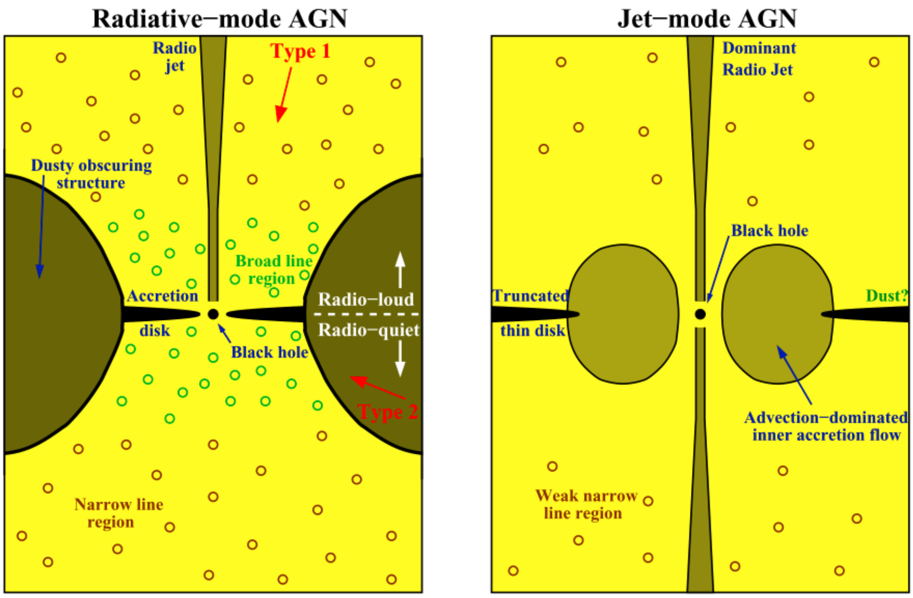

Figure 1.1 – Schematic view (not on scale) of the central regions of radiative-mode and jet-mode AGN, from Heckman & Best (2014). Radiative-mode AGN (left panel) are characterized by an accretion disk, releasing energy via radiation, a dusty obscuring structure called 'torus', and by broad-line and narrow-line emission regions. Some radiative-mode AGN can also produce powerful radio jets. On the other hand, jet-mode AGN (right panel) have an advection-dominated inner accretion flow and a possible truncated accretion disk at larger radii. Most of the output energy is channeled in radio jets and the less significant radiative emission weakly ionizes gas clouds in the narrow-line region.

Radiative-mode AGN

In radiative-mode AGN the central SMBH is accreting material at a high rate ($L_{\rm Bol}/L_{\rm Edd} \gtrsim 1\%$) via an accretion disk. Radiative-mode AGN are usually hosted by moderately massive galaxies (i.e. stellar mass 10^{10}-few 10^{11} $M_\odot$) with a young central stellar population and SMBH masses in the range $10^{6.5}$-10^{8} $M_\odot$. It is important to note that some radiative-mode AGN, associated with high mass SMBH, are able to drive powerful two-sided jets (see Sec. 1.2 for further details) and are radio AGN.

The accretion disk emits a significant amount of radiation in the optical and UV bands and is likely surrounded by a corona of hot electrons, which up-scatter photons up to X-ray energies. The accretion disk and the corona illuminate and heat gas clouds which are located at different distances from the SMBH.

In the plane of the accretion disk, at larger scales, we find dusty material, the so-called torus, which absorbs and collimates the light from the central AGN in the polar direction. The light absorbed by the torus is re-emitted at infrared (IR) wavelengths.

The gas clouds in the very inner regions (sub-pc/pc scales), which are close to the SMBH, form the so-called broad line region (BLR). The gas of these high-density clouds is observed via the emission of permitted hydrogen emission lines, like Hα and Hβ, which are broad (width of several thousands $\rm km\,s^{-1}$) due to the proximity of the SMBH. In Type 2 AGN the orientation of the AGN is such that the torus can obscure the emission from the BLR and the accretion disk. On the other hand, in Type 1 objects the line of sight does not intersect the obscuring material of the torus and it is possible to detect the radiation emitted by the accretion disk and the emission lines of the BLR.

A population of clouds which emits narrow emission lines with a typical width of several hundred $\rm km\,s^{-1}$ is located at larger distances from the SMBH. This is the so called narrow line region (NLR) of the AGN which usually extends up to a few kpc, even though, in some cases, more extended NLR (ENLR) have been observed.

These clouds emit permitted hydrogen lines and, due to the low gas densities, forbidden lines associated with other elements like oxygen, nitrogen or sulfur (e.g. the [O III]$\lambda\lambda$4958,5007Å, [N II]$\lambda\lambda$6548,84Å and the [S II]$\lambda\lambda$6717,6731Å doublets). For some objects, the NLR has a conical shape due to the fact that the ionizing photons of the AGN are collimated by the torus. However, some light has also been found beyond these 'ionization cones' and NLR often have more irregular morphology (see Storchi Bergmann 2015, for a discussion).

The clouds of the BLR and the NLR seems to be intimately linked to the innermost structures of the AGN. In fact, the kinematics of the ionized gas of the NLR has been found to include rotation in the plane of the galaxy and inflow motions (see Storchi Bergmann 2015). In addition, the study of Storchi-Bergmann et al. (2017) showed that the inner part of the BLR seems to coincide with the outer part of the accretion disk.

Jet-mode AGN

Jet-mode AGN accrete material on the SMBH at a low rate ($L_{\rm Bol}/L_{\rm Edd} \lesssim 1\%$) and the accretion process is radiatively inefficient compared to radiative-mode AGN. They are usually hosted by the most massive elliptical galaxies (i.e. stellar mass 10^{11}-10^{12}M$_{\odot}$), generally having a purely old stellar population.

In jet-mode AGN, the accretion disk is either absent or truncated in the inner parts, and the accretion happens via a so-called advection-dominated or radiatively-inefficient accretion flow which is able to launch jets. These jets have initially relativistic velocities, but are slowed down once they start interacting with the surrounding material and the gaseous halo of the host galaxy. Jets can extend to galactic scales or even reach very large scales ($\sim$Mpc), well beyond the host galaxy. They usually inflate lobes of plasma and their non-thermal emission is mainly detected in the radio band (see Sec. 1.2 for further details). The relatively small amount of radiative energy of the AGN can only weakly ionize the sparse population of gas clouds residing in the NLR.

As is evident from the above, observations of AGN at different wavelengths probe different AGN components (i.e. accretion disk, torus, gas clouds, jets) and their physics. This is nicely illustrated by Centaurus A, the closest radio AGN in the southern sky. Centaurus A has been studied for decades in all possible wavebands and fully shows the beauty and, at the same time, the complexity of AGN. As shown in Fig. 1.2, it has large- and small-scale radio jets/lobes and a bright optical AGN which illuminates filaments of gas up to large distances from the galaxy center. The ionized gas filaments shown in the upper left panel of Fig. 1.2 are investigated in detail in Chapter 2, Chapter 3 and Chapter 4 of this thesis.

1.1.2 AGN feeding and feedback: the role of gas

Gas is a fundamental tracer to probe the AGN feeding and feedback. It is the fuel for the AGN activity and, at the same time, is also the component which is most affected by the energy released by the AGN. Gas can be found in the form of molecular (i.e. H_2 usually detected by the cold molecular CO gas associated with this H_2), atomic (i.e. H I) and ionized gas.

The results presented by Riffel et al. (2006, 2008, 2009, 2010); Riffel & Storchi-Bergmann (2011); Storchi-Bergmann et al. (2009, 2010) suggest that, while the ionized gas is ideal to probe AGN-driven outflows, the warm molecular gas is more related to the feeding of the AGN. On the other hand, outflow studies seems to indicate that a significant amount of mass in the outflow resides in the cold phase (see e.g. Tadhunter et al. 2014; Cicone et al. 2014; Fiore et al. 2017). The kinematics of the different gas phases is often very complex to disentangle, with e.g. rotating disks, infalling clouds and outflowing gas which can coexist in a single object (see e.g. Storchi-Bergmann et al. 2010; García-Burillo et al. 2014).

In the following I describe the main processes which have been related to the AGN feeding and (negative and positive) feedback.

Feeding

Gas accretion onto the SMBH is challenging to probe, mainly because it happens on very small scales. In our current understanding, a series of processes carry material towards the central regions (Shlosman et al. 1990; Wada 2004), while the actual SMBH growth is regulated by processes on scales smaller then about 1 kpc (e.g. Hopkins & Quataert 2010).

Radiative-mode AGN essentially trace the population of galaxies where most of the black hole growth is happening (Kauffmann et al. 2003a). There are indications that their host galaxies are distinct from normal galaxies (i.e. not showing signs of AGN activity) mainly due to an abundant central (kpc-scale) supply of cold and dense gas

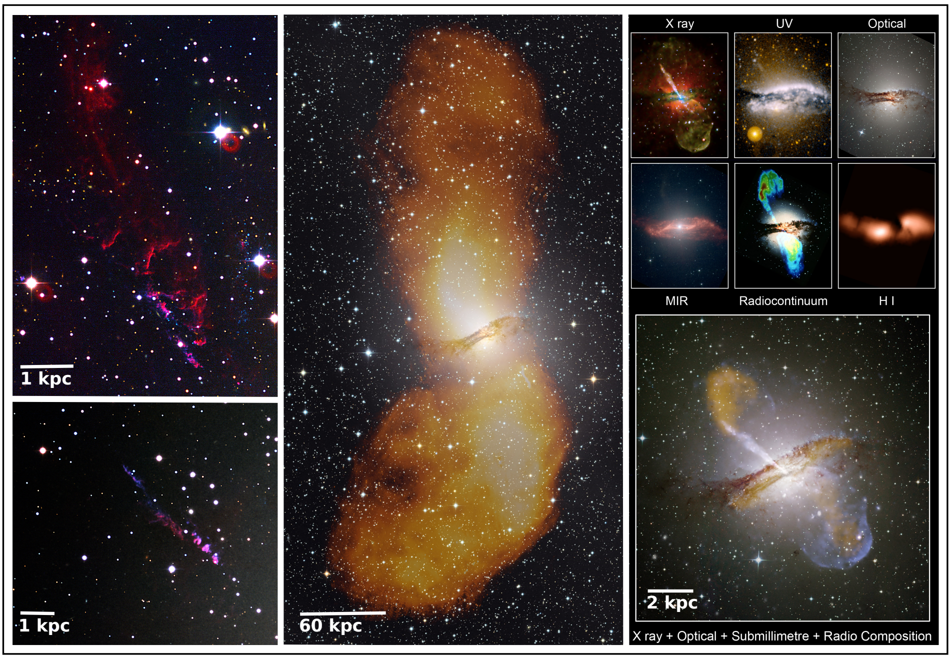

Figure 1.2 – *Left panels.* The so-called inner (lower panel) and outer filament (upper panel) of Centaurus A which consist of multiple clouds/filaments of ionized gas within the extended NLR of the AGN, respectively about 8.5 kpc and 15 kpc away form the galaxy center. Credit: ESO. *Central panel.* Optical/radio composite image of Centaurus A where it is possible to see the large scale radio-emitting lobes (shown as orange) extended on scales of about 250 Kpc. Credit: Capella Observatory (optical), with radio data from I. Feain, T. Cornwell, and R. Ekers (CSIRO/ATNF), R. Morganti (ASTRON), and N. Junkes (MPIfR). *Right panel.* Observations in six different wavebands (upper part) and a composite X-ray, optical, submillimeter, radio image of the central regions of Centaurus A (lower part). The small scale radio-jets, which extend on scales of about 5 kpc, are evident in the radio. A cold gas disk is traced by the atomic H I gas. The emission in the X-rays comes from the nuclear source and its jet and from diffuse hot gas. A dust band over the central part of the galaxy is evident from the optical and the mid-infrared image. Credit: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/J.Van Gorkom/Schminovich et al.), Radio continuum image (NRAO/VLA/J. Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI); Ultraviolet (NASA/JPL/Caltech/SSC); Mid-Infrared (NASA/JPL/Caltech/J.Keene(SSC/Caltech)). Image by Ángel R. López-Sánchez

(Heckman & Best 2014). Galaxy mergers (e.g. Barnes & Hernquist 1996; Hopkins et al. 2008; Ramos Almeida et al. 2011; Couto et al. 2016) and secular processes (e.g. Kormendy & Kennicutt 2004; Combes 2004, 2011) have been suggested to be the main mechanisms to funnel gas towards the central regions (~1 kpc). The study of e.g. Storchi-Bergmann et al. (2003, 2007) reported streaming motions of ionized gas toward the AGN, suggesting this as a possible channel through which matter is transferred from galactic scales to the nuclear region to feed the SMBH.

In radiative-mode AGN, H I atomic gas is usually spread out in large-scale disks, often showing a dip/hole in the center of the galaxy. The H I seems to be unrelated to the feeding of the SMBH and does not show remarkable differences with respect to normal galaxies (e.g. Fabello et al. 2011; Ho et al. 2008). Nevertheless, recent studies started to find circum-nuclear structures of gas and dust in the innermost regions of radiative-mode AGN which are thought to be linked to the AGN feeding. Hicks et al. (2013) found circum-nuclear disks (CND) of H_2 molecular gas with a size of ~200 pc. These nuclear structures also host relatively young stellar populations that imply gas inflows from the surrounding ISM in order to be sustained. Dumas et al. (2007) observed analog structures in the ionized gas phase and it is likely that these are the ionized gas counterpart of the molecular gas CND reported by Hicks et al. (2013). In addition, dust has been used as a proxy to study the cold gas in the center of radiative-mode AGN. The studies of Simões Lopes et al. (2007), González Delgado et al. (2008) and Lauer et al. (2005) found that, compared to normal galaxies, active galaxies show circum-nuclear dust structures on scales up to 1 kpc. In addition, García-Burillo et al. (2016) showed that CND are connected, physically and dynamically, with the AGN torus and Müller Sánchez et al. (2009) found molecular gas streams going from the CND into the AGN nucleus. Whether the central SMBH is fed directly from this supply of nuclear gas or indirectly through smaller scale processes is still unclear.

While radiative-mode AGN are usually hosted by isolated field galaxies (Miller et al. 2003; Kauffmann et al. 2004; Von Der Linden et al. 2007), jet-mode AGN tend to be found in massive ellipticals and in the central galaxies of groups or clusters (Best 2004; Reviglio

& Helfand 2006; Sabater et al. 2013). This suggest a different mechanism for the fueling of the AGN.

Hot gas, in the halo of the host galaxies or whitin the intra cluster medium (ICM), has been argued to be the fueling source of jet-mode AGN (e.g. Hardcastle et al. 2007). Direct accretion of hot gas was initially suggested by Bondi (1952), but does not provide the required jet powers for the most luminous radio AGN (e.g. Cao & Rawlings 2004; McNamara et al. 2011). It seems more plausible that the hot gas cools down prior to accretion.

Numerical simulations have shown that cooling can occur in the gas of the hot halo and that, through this, clouds and filaments of cold gas can enter a quasi free-fall regime (see e.g. Gaspari et al. 2013). This induces chaotic collisions which make the clouds lose angular momentum, triggering a series of small-scale, randomly oriented, accretion events which are able to stimulate the AGN activity. Fabian (2012) showed that the cooled gas is mainly in the form of clouds and filaments of cold molecular gas, extending up to tens of kpc in cluster environments. An alternative gas source, in less massive elliptical galaxies hosting jet-mode AGN, can be material from stellar mass loss (Hillel & Soker 2013).

Processes related to the AGN feeding have been studied using the warm molecular H_2 and the ionized gas in Chapter 5 and Chapter 6 of this thesis.

Negative Feedback

The energy output of an AGN is able to affect the ionization and kinematics of the gas at both small and large scales (see the review by Fabian 2012). Depending on the main AGN energy output channel (i.e. radiation or jets), feedback comes in two flavors, radiative and mechanical. Radiative feedback is typical of radiative-mode AGN and is driven by radiation winds rising form the accretion disk around the SMBH. Mechanical feedback is typical of jet-mode AGN and is driven by the expansion of the radio jets which inject kinetic energy into the surrounding ISM. In the global picture, radiative and mechanical AGN feedback operate on different scales and affect different gas phases.

There is ample evidence that radiative-mode AGN are driving gas outflows (see e.g. Alexander et al. 2010; Cicone et al. 2014; Rupke et al. 2017). Observations have shown that AGN-driven winds act mainly at galaxy-scales (kpc/sub-kpc) on the cold phase of the ISM, while their relevance on larger scales is still controversial (Zakamska et al. 2004; Greene et al. 2011; Liu et al. 2013a,b). Radiative-mode AGN form the majority of the AGN population (Best et al. 2005) and are hosted by galaxies that are currently evolving by increasing their mass (see Sec. 1.1.1). Radiative feedback is thought to be the most common way to quench star formation in these galaxies, stop their evolution and create 'red and dead' elliptical galaxies. Direct observational evidence for this is still lacking, even though suggestive correlations between radiative feedback and star formation have been found (e.g. Farrah et al. 2012; Wylezalek & Zakamska 2016; Baron et al. 2017).

On the other hand, AGN mechanical feedback is clearly seen in action on larger scales (10-1000 kpc) excavating cavities in the hot gas halo of galaxy clusters/groups and of giant elliptical galaxies. Jet-mode AGN are preferentially hosted by massive galaxies with old stars and the mechanical feedback is thought to prevent further gas accretion, keeping the host galaxy 'red and dead' (McNamara & Nulsen 2012). However, radio jets can also operate on smaller, galactic scales and, in the same way as AGN winds, have been discovered to drive gas outflows (see e.g. Nesvadba et al. 2006, 2007, 2008; Ho 2008). More details on the effect of AGN mechanical feedback at different scales are reported in Sec. 1.2.

Positive Feedback

The ability of the AGN feedback to compress and stimulate the cooling of gas has been connected to the triggering of the star formation activity (e.g. van Breugel et al. 1985; Rejkuba et al. 2002; Privon et al. 2008; Zinn et al. 2013; Maiolino et al. 2017). Since the first observational evidence of positive feedback, many theoretical studies have been conducted to test the environment in which this process can happen, its efficiency and its importance in a cosmological context (De Young 1989; Rees 1989; Gaibler et al. 2012; Ishibashi & Fabian 2012; Silk 2013; Bieri et al. 2015; Wagner et al. 2016; Fragile et al. 2017). Observational evidence of positive feedback is sparse in the literature, mainly due to the fact that good spatial resolution is needed to detected this process. With the advent of integral field (IFU) spectroscopy the number of reported cases of positive feedback is increasing.

Positive feedback has shown its relevance especially in radio galaxies at low redshifts where it is also known as 'jet-induced star formation'. Among the most famous sources showing jet-induced star formation are Minkowski's Object (Brodie et al. 1985; van Breugel et al. 1985; Croft et al. 2006; Lacy et al. 2017), Centaurus A (e.g. Mould et al. 2000; Oosterloo & Morganti 2005; Crockett et al. 2012) and the companion of the quasar HE0450-2958 (Elbaz et al. 2009). In these AGN, enhanced star formation has been observed at the edges of the expanding radio plasma jets/lobes at large distances from the optical galaxy. The case of Centaurus A is treated in detail in Chapter 2, Chapter 3 and Chapter 4 of this thesis.

At higher redshift, positive feedback has been used to explain the so-called 'alignment effect' between the optical and radio emission in high-luminosity radio AGN (Chambers & Miley 1990; Best et al. 1996; Dey et al. 1997; Lacy et al. 1999; Clements et al. 2009; Zinn et al. 2013; Gullberg et al. 2016). In addition, it has been shown that star formation can be triggered via the compression of gas clouds in galactic disks (Cresci et al. 2015a,b), and even within outflowing material (Maiolino et al. 2017).

However, the star formation rates and efficiencies derived from the few known cases can differ significantly and, to date, it is still not possible to draw robust conclusions on the efficiency of positive feedback and its role in the context of galaxy evolution. More details on this topic can be found in Chapter 4 of this thesis.

1.2 Radio galaxies

In the radio band, AGN are identified by means of their non-thermal synchrotron emission due to the relativistic motion of charged particles under the influence of magnetic fields. Radio AGN generally consist of a radio core, located at the center of the host galaxy, which is connected to extended and diffuse lobes inflated by synchrotron-emitting jets (see Miley 1980, for a review). Radio AGN represent a key sub-class of the entire AGN population (15-20%, see Kellermann et al. 1989). They are preferentially hosted by very massive elliptical galaxies and have a pivotal role in tracing their evolution (see Tadhunter 2016a, and references therein). Most of our knowledge about radio AGN concerns objects with high radio powers ($P_{1.4GHz} > 10^{24}\,\mathrm{W\,Hz^{-1}}$). However, there is an entire population of radio AGN with lower radio powers whose detailed radio and optical morphologies still have to be explored.

As already mentioned in Sec. 1.1.1, not only jet-mode AGN but also radiative-mode AGN are able to launch jets, which during their expansion deposit mechanical energy in the ISM of the host galaxy. The radio AGN population is mostly composed of jet-mode AGN. However, the radiative-mode radio AGN population becomes dominant at high radio powers ($P_{1.4GHz} \gtrsim 10^{26}\,\mathrm{W\,Hz^{-1}}$).

In this thesis I investigate radio AGN observed at high inclination angles (i.e. Type 2 AGN) which are classically referred to as Radio Galaxies. Two main classes of radio galaxies have been defined by Fanaroff & Riley (1974) based on the morphology of the radio emission. Radio galaxies with collimated jets, showing high surface brigthness compact regions within their lobes, called hot spots, have been named FRII or 'edge brightened', because the brightest radio features are distant from the core of the radio source. They are mostly associated with radiative-mode AGN (accreting at high rates) and tend to show strong emission lines from ionized gas in their optical spectra. On the other hand, there are radio sources with turbulent and bright jets which have less defined radio lobes (often resembling plumes) and no hot-spots. These sources, called FRI or 'edge darkened', are connected to mechanical-mode AGN (accreting material at low rates) and show weaker emission lines in the optical band. In general, highly collimated jets have little interaction with the surrounding medium while turbulent jets, entraining material along their path, are thought to be more efficient in disturbing the surrounding gas (e.g. Mukherjee et al. 2016; Massaglia et al. 2016).

Based on the relative strength of the ionized gas emission lines in BPT diagrams, radio galaxies have been divided into high-excitation and low-excitation sources (see Best & Heckman 2012, and references therein) which, respectively, overlap quite well with the FRII and FRI classes.

The mechanical feedback of the radio jets can operate on different scales and on different gas phases, mainly depending on the power and collimation of the radio jets, and on the characteristics of the surrounding medium.

As already mentioned describing AGN negative feedback in Sec. 1.1.2, the best examples of AGN mechanical feedback are observed in galaxy clusters. Here, radio jets, connected to the massive elliptical galaxy sitting at the center of the cluster, can extend to large scales (of the order of Mpc) and excavate cavities within the hot gas of the ICM. These jets prevent the cooling of the hot ICM gas and, thus, the host galaxy from forming new stars. This kind of AGN feedback, also know as 'maintenance mode' feedback, maintains the host galaxy 'red and dead' and it is essential to explain the shape of the high luminosity end of the galaxy luminosity function (e.g. Benson et al. 2003b; McNamara & Nulsen 2007).

In line with this, in the past, models have investigated the effect of AGN mechanical feedback mainly in the context of galaxy groups and clusters (Bower et al. 2006b; Croton et al. 2006; Sijacki et al. 2007). On the other hand, AGN feedback on galactic scales has been often implemented in the form of radiative feedback from winds (Di Matteo et al. 2005; Springel et al. 2005; Hopkins et al. 2006; Debuhr et al. 2010; Choi et al. 2014) while the relevance of jets has remained largely unexplored.

Recently, Cielo et al. (2017) compared the effect of AGN feedback by radiation and by collimated jets on a clumpy galactic disk. Their results show that, while the radiation mainly heats and rarifies the gas, radio jets drive the more powerful outflows (especially when their inclination is such that they intercept material of the disk), and have a stronger mass and momentum coupling with the dense gas. Moreover, Weinberger et al. (2017) implemented both the radiative and the mechanical AGN feedback modes in the context of the Illustris cosmological simulation (Vogelsberger et al. 2014). Interestingly, they find that a large fraction of the kinetic energy, injected by the AGN via the radio jets, is transmitted to the ISM via shocks. This provides a distributed heating channel that affects the ISM of the host galaxy and can efficiently quench the star formation on galactic scales.

1.2.1 Compact and young radio galaxies

An ideal class of radio galaxies which can be used to study the importance of the mechanical feedback on galactic scales are the so-called 'compact radio galaxies'. These are radio galaxies that show intrinsically small-scale radio jets (in the order of kpc and below) which are still embedded in the host galaxy. Compact and young radio galaxies are AGN whose activity has been recently triggered and whose radio jets/lobes are expanding within the dense, cold ISM of their host galaxies. These sources are thought to represent the first evolutionary stages of the classical extended radio galaxies (i.e. FRI and FRII).

Results coming from different sets of simulations confirmed the crucial role the radio plasma has in disturbing the ISM in compact radio galaxies. The simulations of small-scale jets by e.g. Saxton et al. (2005), Sutherland & Bicknell (2007) and Wagner & Bicknell (2011) have shown that an overpressured jet can inflate a cocoon which drives a quasi-spherical energy bubble into the ISM. These simulations have also found that the injected energy is more effective in disturbing the surrounding gas when the jet encounters inhomogeneities in the ISM. Furthermore, Wagner & Bicknell (2011) and Wagner et al. (2012) stressed the importance of proper ISM modeling by simulating compact radio galaxies with powerful relativistic jets interacting with a two-phase ISM consisting of hot gas in which dense clouds of warm gas are embedded. They found that the size of the cold gas clouds is one of the main parameters determining the effect the jet has on the overall ISM. Smaller clouds are easier to disperse (i.e. negative feedback) while bigger clouds are more subject to induced collapse (i.e. positive feedback).

Compact and young radio galaxies are characterized by convex radio spectra due to synchrotron self absorption at low frequencies (Fanti 2009). They are divided in three different sub-classes, namely compact steep spectrum (CSS), GHz-peaked spectrum (GPS) and high frequency peaked (HFP) sources. The main difference between the three classes is the different peak frequency of the radio spectrum which is related to a different source size (Snellen et al. 2000). Compact source have small sizes, do not go beyond 10-20 kpc, and have estimated radio ages lower than few 10^5 yr (Murgia et al. 1999). The age of the radio source is usually estimated by modeling the spectrum of the radio continuum (radiative age, see e.g. Murgia et al. 1999) or by monitoring the small-scale jets expansion over time with high resolution very long baseline interferometry (VLBI) observations (kinematical age, see e.g. Giroletti & Polatidis 2009).

Most of the current evidence indicates that compact peaked-spectrum radio sources are intrinsically young ('youth scenario', Giroletti & Polatidis 2009; Murgia et al. 1999; Murgia 2003), even though in some cases their small size can be explained with a very dense ISM which prevents their growth ('frustration scenario', Orienti & Dallacasa 2008; Tingay et al. 2015; Callingham et al. 2015).

For the great majority of AGN with intrinsically compact radio morphologies (i.e. compact radio cores with no diffuse emission) known nowadays it is not possible to derive the age of the radio source due to the lack of multi-frequency radio observations and/or detailed VLBI studies.

These newly born radio AGN, which are expanding within a dense ISM, are ideal tracers of the AGN feeding and feedback activity. In fact, they hosts small scale/circum-nuclear disks of H I (Pihlström et al. 2003) and molecular gas (CO and H_2, García-Burillo et al. 2007; Labiano et al. 2013; Geréb et al. 2015; Maccagni et al. 2017) which seem to be connected to the triggering of the AGN activity. Moreover, the effect of the AGN feedback, mainly related to the expansion of the radio jets, is also prominent in these class of sources. Ionized gas outflows are commonly detected in compact, young radio sources, and have more extreme kinematical features compared to those observed in extended radio sources (Holt et al. 2008). Also the atomic (H I) and molecular (warm H_2 and cold CO) gas often shows signs of outflows (e.g. Dasyra & Combes 2012; Geréb et al. 2015; Struve & Conway 2012; Gupta et al. 2006; Chandola et al. 2011). In addition, some of the most famous examples of multi-phase AGN-driven outflows are found among compact radio galaxies (see e.g. the study of Tadhunter et al. 2014; Dasyra & Combes 2012).

Compact radio galaxies also offer the ideal conditions (i.e. the AGN is strongly interacting with the ISM in which it is still embedded) to probe the occurrence and relevance of shocks associated with AGN-driven outflows. Shocks might be crucial for both the gas ionization and kinematics (see e.g. Dopita & Sutherland 1995; Reynaldi & Feinstein 2013; Sutherland et al. 1993; Couto et al. 2017) and, as indicated by the simulation of Weinberger et al. (2017), for the energy transfer from the AGN to the ISM. Indications of the presence of shocks have often been reported for compact radio sources and they are usually connected to the expansion of the radio source within the ambient ISM (de Vries et al. 1997; Holt et al. 2008; Morganti et al. 2013; Tadhunter et al. 2014).

The effect of AGN negative feedback in compact radio galaxies is investigated in Chapter 6 and Chapter 7 of this thesis.

1.3 The complex nature of AGN-driven outflows

Outflows are almost ubiquitous in luminous AGN, they are detected in different gas phases (ionized, atomic and molecular gas) and at different scales, going from the very central regions of the host galaxies (less then 1 pc) up to super-galactic scales (tens of kpc).

There are indications that the radio properties of AGN, and especially their radio power, are intimately connected to the kinematics of the ISM on kpc scales. By studying a large sample of optically selected AGN, Mullaney et al. (2013) found that compact radio galaxies (i.e. extended to kpc scales or less) play a major, if not the dominant, role in strongly disturbing the ionized ISM. In addition, Geréb et al. (2015) and Maccagni et al. (2017) showed evidence that H I gas with disturbed kinematics is preferentially found in compact radio galaxies.

The actual impact outflows have on the star formation rates of their host galaxies is still a matter of debate (Woo et al. 2017; Wylezalek & Zakamska 2016). There have been cases where a spatial anti-correlation between outflowing gas and star formation has been reported (Cano-Díaz et al. 2012; Cresci et al. 2015a; Carniani et al. 2016), showing that outflows are able to quench the star formation along their path. However, it seems that outflows have no effect on the star formation happening outside their zone of influence. In addition, the ratio between the gas that is actually expelled and the gas that falls back onto the host galaxy is still uncertain (Arribas et al. 2014).

1.3.1 Outflows in different gas phases

In what follows I describe outflows in the molecular, atomic and ionized gas phases together with their features, the observational techniques and the main results presented in the literature. Each gas phase is associated with a specific observational technique and carries a different piece of information on the outflow driving mechanism, and on the effect this mechanism has on the host galaxy. To date, many observations of outflows have been carried out in different bands, but it is still unclear how and whether the different phases of the outflowing gas are related to each other.

In particular, the discovery of atomic and molecular gas outflows in the last decades has been a surprise considering that AGN feedback was expected to heat up gas within the ISM. A scenario which gained more credit in recent years predicts that molecules forms in-situ and, in particular, in the post-shock regions of the outflows. This scenario is supported by observations (e.g Morganti et al. 2015; Simionescu et al. 2018) and by recent simulations (Richings & Faucher-Giguere 2017). This topic is further explored, in the context of compact radio galaxies, in Chapter 6 of this thesis.

A gas outflow and its impact on the host galaxy are usually characterized via three main quantities: the mass outflow rate $\dot{M}$ [$M_{\odot}$yr $^{-1}$], the outflow power $\dot{E}$ [erg s^{-1}] and the outflow efficiency $\dot{E}/L_{\rm Bol}$. The latter is the energy that is used to drive the outflow with respect to the AGN bolometric luminosity which is indicative of the AGN accretion power.

- **Ionized gas outflows**

  Due to the abundance of observational facilities in the optical band and the recent advent of the integral field (IFU) spectroscopy, one of the most common ways to trace outflows has been via their ionized gas phase. Ionized gas outflows are commonly detected via the the [O III]λ5007Å emission line in optical spectra of nearby AGN, or in the near-IR spectra of AGN at higher redshifts. The [O III] emission is usually a strong spectral feature which originates from ionized gas clouds in the NLR of the AGN. Outflows are identified via broadened (usually line widths >500 km s^{-1}) and asymmetric [O III] profiles. Broad [O III] lines (∼1000 km s^{-1}) are almost ubiquitous in objects with sufficiently high AGN luminosities (Brusa et al. 2015; Bischetti et al. 2017; Westmoquette et al. 2012; Rodríguez Zaurín et al. 2013). It is often difficult to estimate the physical size of these outflows, even though, in most of the cases, they seem limited to the inner 1 kpc of the host galaxy (see e.g. Husemann et al. 2016). The density of the ionized gas is another quantity subject to large uncertainties, mainly due to the limitation of the classical line-ratio diagnostics (Holt et al. 2011; Rose et al. 2017). Despite the clear observational evidence of these outflows, it is, therefore, usually difficult to give constraints on their mass and efficiency (see Tadhunter 2016b, for a discussion).

  Radio galaxies seem to drive the most powerful and extended outflows of ionized gas. Mullaney et al. (2013) showed that, for an optically selected sample of AGN, ionized gas with extreme kinematics ([O III] line width >1000 km s^{-1}) is detected only for sources with radio powers $P_{1.4GHz} > 10^{23}$ W Hz^{-1}. In addition, Holt et al. (2008) found that young and compact radio sources are able to drive outflows that are more extreme, in terms of their kinematics, with respect to the outflows of extended radio sources. Concerning the extent of the outflows, the studies by e.g. Husemann et al. (2016) and Harrison et al. (2014) showed that ionized gas outflows that are extended on large scales (>1 kpc) are preferentially found in sources showing radio jets. Recently, Nesvadba et al. (2017) reported very extended (>5 kpc) ionized gas outflows that are clearly spatially coincident with expanding jets of the radio sources.

- **Atomic gas outflows**

  In the local Universe, atomic gas outflows are detected via two main tracers, namely the sodium (NaI D) and the neutral hydrogen (H I) spectral lines. The NaI D is an optical absorption line, detected against the stellar continuum of the host galaxy, which traces the dusty warm atomic gas phase. Once the stellar continuum of the galaxy has been subtracted, outflows are identified by the residual broad and/or blueshifted features of the NaI D line. NaI D outflows usually extend up to a few kpc and, in some cases, they have a conical morphology (see the work by Rupke et al. 2005; Rupke & Veilleux 2013; Rupke et al. 2017; Cazzoli et al. 2016; Lehnert et al. 2011).

  Lehnert et al. (2011) detected NaI D outflows in a sample of extended radio galaxies showing that 1-10% of the jet mechanical energy is needed to power the gas outflows, which have a typical mass outflow rate of about 10 $M_{\odot}yr^{-1}$. Similar estimates have been found tracing the atomic gas via the 21 cm H I line.

  In radio galaxies, atomic gas outflows can be studied via the absorption of the H I against the source radio continuum. Spatially resolved studies have shown that these outflows are often co-spatial with radio lobes/jets (extending to scales $\geq$10 kpc) and, in some cases, their velocity matches with the outflowing ionized gas (see Morganti et al. 2005b,a; Mahony et al. 2016). H I absorption studies have also shown the presence of outfowing gas in the nuclear regions (typically below 1 kpc) of powerful radio sources with a compact radio morphology (Geréb et al. 2014, 2015).

  Teng et al. (2013) found H I outflows reaching extreme velocities (1000 $km\,s^{-1}$) and mass outflow rates (1000 $M_{\odot}yr^{-1}$) in the case of radio galaxies classified as ultraluminous infrared galaxies (ULIRG). This is a class of more extreme AGN, where the host galaxy underwent a merging event which is thought to have stimulated both starburst and AGN activity.

- **Molecular gas outflows**

  Molecular gas outflows are usually detected on sub-kpc/kpc scales via the broadening and asymmetry of the H_2 and CO emission lines.

  The H_2 emission lines, detectable in the rest-frame near-IR band, have been used to trace the warm molecular outflowing gas (e.g. Tadhunter et al. 2014; Emonts et al. 2017). This gas phase is usually difficult to observe and has been suggested to be a transitional phase formed while AGN-heated gas cools down in the form of cold molecular gas (Tadhunter et al. 2014).

  Cold molecular gas outflows are traced using mainly the CO emission line (e.g. Feruglio et al. 2010; Aalto et al. 2012; García-Burillo et al. 2014; Cicone et al. 2014; Feruglio et al. 2015, 2017) and the OH absorption line (e.g. Sturm et al. 2011; Veilleux et al. 2013), especially since the advent of the Atacama Large Millimeter Array (ALMA) which allowed us to extend outflow studies to the mm/sub-mm regime. Most of the current studies on molecular gas outflows focus on ULIRG and this might explain also the high mass outflow rates (10-100 $M_{\odot} yr^{-1}$) and efficiencies (1-5%) that are usually found (e.g. Cicone et al. 2014; Emonts et al. 2017).

  Even though the statistics is more limited, in the case of radio galaxies, cold molecular gas outflows have been associated with expanding radio jets (Matsushita et al. 2007; Krause et al. 2007; Dasyra & Combes 2012; Morganti et al. 2015; Oosterloo et al. 2017).

There are only a few examples of AGN (e.g. IC 5063, Mrk 231, PKS 1345+12, 3C 305), mainly related to compact radio galaxies, where the synergy between observations in the different bands fully revealed the multi-phase nature of an outflow (Tadhunter et al. 2014; Feruglio et al. 2015; Morganti et al. 2005a; Dasyra & Combes 2012). As it is shown in Fig. 1.3 for the case of IC 5063, in these AGN the different gas phases have similar kinematics indicating that they are tracing a single physical structure.

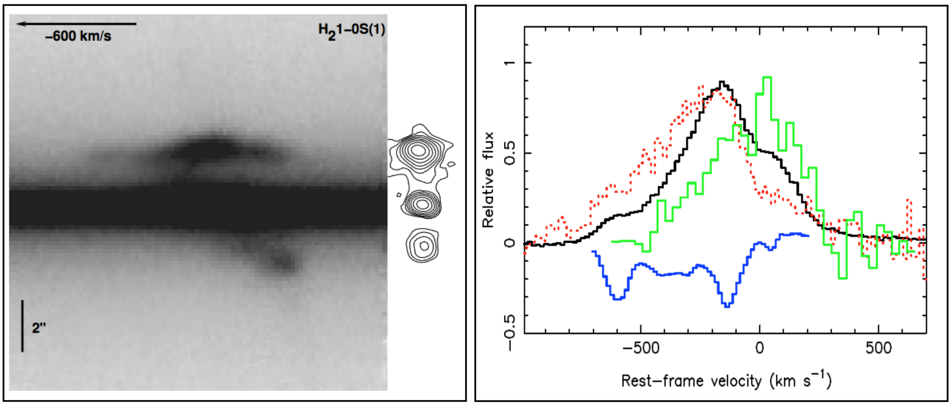

Figure 1.3 – The multi-phase outflow in the radio galaxy IC 5063 from the work of Tadhunter et al. (2014). *Left panel.* Grey-scale representation of the near-IR long-slit spectrum of IC 5063, covering a wavelength range centered on the H_2 1-0S(1) emission line of the warm molecular gas. For comparison, a scaled version of the 1.4 GHz radio map of the source is presented to the right. It is possible to notice the disturbed kinematics of the H_2 gas that is spatially associated with the jets of the radio galaxy. *Right panel.* Emission and absorption lines from different gas phases in arbitrary fluxes. Warm molecular (H_2 1-0S(1), black solid line) and ionized (Brγ, red dotted line) gas velocity profiles for the western radio lobe of IC 5063 (i.e. upper radio lobe of the radio source in the left panel) are compared with the spatially-integrated atomic gas absorption (H I, blue solid line) and cold molecular gas (CO(2-1), green solid line) velocity profiles. It is possible to see that there is a good overlap between the velocities spanned by the different gas phases.

Our understanding is more limited in the case of extended samples of objects, mainly due to the lack of multi-wavelength observations with comparable spatial scales. In Chapter 7 of this thesis we expand the discussion of this topic by carrying out an investigation on the ionized and atomic gas in a sample of radio galaxies.

Fiore et al. (2017) collected information from the literature (for sub-kpc/kpc scales outflows), trying to uniform the measurement of the mass outflow rate and outflow efficiency for the main samples/cases of outflows known in the different gas phases. They find indications that molecular outflows carry a significant amount of mass and show higher outflow efficiencies (with an average efficiency of 2.5%) compared to ionized gas outflows (0.16-0.3%). However, due to selection biases, their result is not conclusive and needs a better knowledge of the physical properties of multi-phase outflows to be confirmed.

1.4 This Ph.D. Thesis

In this Ph.D. thesis, I address some of the open questions related to the interaction between the energy released by the AGN and the host galaxy ISM. This is done by studying, with different observational techniques, the ionized and warm molecular gas in radio galaxies. In particular, I use nearby radio galaxies to study the effect of the radio plasma on the ISM on galactic scales.

Spatially resolved observations allow us to investigate, and appreciate, the complexity of the AGN-ISM interaction. The closest radio galaxies are unique laboratories where it is possible to test the physics of the coupling of jet mechanical energy to the surrounding medium and distinguish it from the effects of the radiation from the central AGN. Furthermore, as discussed in Sec. 1.1.2, they are ideal to disentangle possible positive effects of the AGN feedback e.g. the jet-induced star formation.

As described in Sec. 1.1.2, the ISM of active galaxies is a challenging environment to study. This is due to the fact that gas is connected to both the AGN feeding and feedback. From one side, it is still unclear which are the processes and the gas phases involved in the SMBH feeding. IFU observations of cold gas in the central regions of AGN have the potential to shed light on this.

From the other side, AGN feedback can be traced by the presence of gas outflows. However, quantifying the impact outflows have on the host galaxies requires deriving reliable estimates for the outflow mass rate and the outflow efficiency. An accurate measurements of the gas density is crucial for this purpose and to understand whether the AGN feedback efficiencies predicted by cosmological simulations are realistic.

How and whether the different gas phases are related is still a matter of debate and multi-wavelength information is available only for a handful of objects. Observations spanning a broad spectral range can give access to multiple spectral lines and allow us to explore the possibility of an evolutionary scenario for the different gas phases, as suggested by some observations and numerical simulations. In addition, they can constrain the occurrence and the effect of shocks which are thought to be a key process at play in outflows.

However, the results obtained with detailed studies of single objects need to be confirmed by statistical studies. It is still unclear weather some gas phases preferentially trace AGN feeding or AGN feedback, or whether they are equally involved in both. Using some of the available surveys in the literature it is now possible to start to investigate this topic.

These are the main topics that are addressed, in more detail, in the various chapters of this thesis.

1.4.1 Thesis outline

In the first chapters, I study the so-called outer filament of Centaurs A to probe warm ionized gas under the influence of a radio jet. The outer filament is a complex of ioinzed gas clouds located in the extended NLR of Centaurus A, about 15 kpc away from the center of the galaxy. Centaurus A has been at the center of innumerable studies in the last decades and, due to its proximity, offers one of the clearest examples of an interaction between a radio jet and multi-phase gas clouds. I take advantage of new IFU observations to study the warm ionized gas and its relation with the atomic gas.

- In **Chapter 2** and **Chapter 3** I study the signatures of the jet-ISM interaction in the outer filament, expanding on previous results obtained from the H I. I use integral field VIMOS observations of a limited region of the warm ionized gas and, then, expand the investigation by observing a larger portion of the outer filament with MUSE. These observations allow me to study the ionization state and the kienematics of the gas across the entire outer filament and relate these to the nearby cloud of H I for which signs of a jet-ISM interaction have been previously reported.

- In **Chapter 4** I take advantage of the spatial resolution of the MUSE data to study a specific region of the outer filament where star formation is occurring. I quantify the star formation efficiency and I use line-ratio diagnostics to study the complex effect the star formation, together with the AGN ionizing radiation, has on the ionization of the surrounding gas.

My study continues by probing the AGN feeding and feedback mechanisms in young radio galaxies. I use two prototypical young radio galaxies, PKS B1718-649 and PKS B1934-63, to study the conditions of the warm molecular and warm ionized gas, the relation between these two gas phases and the efficiency of the AGN feedback mechanism.

- In **Chapter 5** I present SINFONI near-infrared IFU observations of the warm molecular gas (H_2) in the inner 2.5 kpc region of PKS B1718-649, a newly born radio AGN. I study the distribution and the kinematics of the molecular gas in relation to the atomic gas phase, with particular attention to the feeding mechanism of the SMBH.

- In **Chapter 6** I use X-shooter slit spectroscopic observations to study the multi-phase ISM in the the young radio galaxy PKS B1934-63, where an ionized gas outflow has been previously reported to be present. The good velocity resolution and spectral coverage of the data allows me to probe the kinematics of the warm ionized and warm molecular gas in more detail, and investigate the presence of shocks driven by the AGN feedback. In addition, I use a new technique to determine the gas density and give a more robust estimate of the mass outflow rate and outflow efficiency for the warm ionized gas. By integrating my results with information from the literature, I also outline a possible evolutionary sequence for young radio galaxies and test the scenario in which cold gas is formed within outflows.

Finally, I extend my investigation to the ISM of a sample of radio galaxies to have a broader view on the occurrence of different gas phases and their relation with AGN-driven outflows and/or with the feeding of the AGN.

- In **Chapter 7**, I consider a sample of about 250 radio galaxies, spanning a significant range of radio powers, and I study the kinematics of the warm ionized gas by analyzing SDSS spectroscopic data. Thanks to previous observations tracing the H I gas, I can study the relation between the ionized and atomic gas phases and their kinematics. In addition, I relate the occurrence of ionized gas to the H I content and to the radio and IR properties of these galaxies.

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"One forges one's style
on the terrible anvil of daily deadlines."
Émile Zola

"Si forgia il proprio stile
sulla terribile incudine delle scadenza quotidiane."
Émile Zola